NANOTECHNOLOGY

Prepared Written Statement and Supplemental Material of R. E. Smalley, Rice University, June 22, 1999

Mr. Chairman, I appreciate the opportunity today to present my views on nanotechnology. There is a growing sense in the scientific and technical community that we are about to enter a golden new era. We are about to be able to build things that work on the smallest possible length scales, atom by atom with the ultimate level of finesse. These little nanothings, and the technology that assembles and manipulates them -- nanotechnology -- will revolutionize our industries, and our lives.

Everything we see around us is made of atoms, the tiny elemental building blocks of matter. From stone, to copper, to bronze, iron, steel, and now silicon, the major technological ages of humankind have been defined by what these atoms can do in huge aggregates, trillions upon trillions of atoms at a time, molded, shaped, and refined as macroscopic objects. Even in our vaunted microelectronics of 1999, in our highest-tech silicon computer chip the smallest feature is a mountain compared to the size of a single atom. The resultant technology of our 20th century is fantastic, but it pales when compared to what will be possible when we learn to build things at the ultimate level of control, one atom at a time.

Nature has played the game at this level for billions of years, building stuff with atomic precision. Every living thing is made of cells that are chock full of nanomachines - proteins, DNA, RNA, etc.- each jiggling around in the water of the cell, rubbing up against other molecules, going about the business of life. Each one is perfect right down to the last atom. The workings are so exquisite that changing the location or identity of any atom would cause damage. Over the past century we have learned about the workings of these biological nanomachines to an incredible level of detail, and the benefits of this knowledge are beginning to be felt in medicine. In coming decades we will learn to modify and adapt this machinery to extend the quality and length of life. Biotechnology was the first nanotechnology, and it has a long way yet to go.

Let me give you just one, personal, example: cancer. I sit before you today with very little hair on my head. It fell out a few weeks ago as a result of the chemotherapy I've been undergoing to treat a type of non-Hodgkin's lymphoma – the same sort that recently killed King Hussein of Jordan. While I am very optimistic, this chemotherapy is a very blunt tool. It consists of small molecules which are toxic – they kill cells in my body. Although they are meant to kill only the cancer cells, they kill hair cells too, and cause all sorts of other havoc.

Now, I'm not complaining. Twenty years ago, without even this crude chemotherapy I would already be dead. But twenty years from now, I am confident we will no longer have to use this blunt tool. By then nanotechnology will have given us specially engineered drugs which are nanoscale cancer-seeking missiles, a molecular technology that specifically targets just the mutant cancer cells in the human body, and leaves everything else blissfully alone. To do this these drug molecules will have to be big enough – thousands of atoms -- so that we can code the information into them of where they should go and what they should kill. They will be examples of an exquisite, human-made nanotechnology of the future. I may not live to see it. But, with your help, I am confident it will happen. Cancer – at least the type that I have – will be a thing of the past.

Powerful as it will be, this bio-side of nanotechnology that works in the water-based world of living things will not be able to do everything. It cannot make things strong like steel or conduct electricity with the speed and efficiency of copper or silicon. For this, other nanotechnologies will be developed – what I call the "dry side" of nanotech. My own research these days is focused on carbon nanotubes – an outgrowth of the research that led to the Nobel Prize a few years ago. These nanotubes are incredible. They are expected to produce fibers 100 times stronger than steel at only 1/6th the weight – almost certainly the strongest fibers that will ever be made out of anything -- strong enough, even, to build an elevator to space. In addition they will conduct electricity better than copper, and transmit heat better than diamond. Membranes made from arrays of these nanotubes are expected to have revolutionary impact in the technology of rechargeable batteries and fuel cells, perhaps giving us all-electric vehicles within the next 10-20 years with the performance and range of a Corvette at a fraction of the cost.

As individual nanoscale molecules, carbon nanotubes are unique. They have been shown to be true molecular wires, and have already been assembled into the first single molecule transistor ever built. Several decades from now we may see our current silicon-based microelectronics supplanted by a carbon-based nanoelectronics of vastly greater power and scope.

It's amazing what one can do just by putting atoms where you want them to go.

Recently an Interagency Working Group on Nano Science, Engineering and Technology (IWGN) has studied the field of nanotechnology in detail, and made its recommendation to OSTP (March 10, 1999) for a new national initiative in this critical emerging area. Quoting from Mike Roco, chair of the IWGN:

"A national initiative, '*Nanotechnology for the Twenty-First Century: Leading to a New Industrial Revolution*' is recommended as part of the fiscal year 2001 budget. The initiative will support long-term nanotechnology research and development, which will lead to breakthroughs in information technology, advanced manufacturing, medicine and health, environment and energy, and national security. The impact of nanotechnology on the health, wealth, and lives of people will be at least the equivalent of the combined influences of microelectronics, medical imaging, computer-aided engineering and man-made polymers developed in this century. The proposed level of additional annual funding doubles (by $260M) the current level of effort, incrementally increased over three years. This initiative will focus on fundamental research on novel phenomena, processes and tools; synthesis and processing by design; nanostructured devices, materials and systems that are high-risk, broadly-enabling and are designed to have major impact; as well as on education and training of future nanotechnology workers and rapid knowledge and technology transfer."

Mr. Chairman, Honorable Congressmen, I believe it is in our Nation's best interest to move boldly into this new field.

As additional background material, the following is excerpted from "*Nanotechnology – A Revolution in the Making -- Vision for R&D in the Next Decade*," a report of the Interagency Working Group on Nanoscience, Engineering, and Technology, presented to the OSTP Committee on Technology, March 10, 1999.

NANOTECHNOLOGY – A REVOLUTION IN THE MAKING

- VISION FOR R&D IN THE NEXT DECADE

Draft - Executive Summary - Draft

Recommendation:

As part of the fiscal year 2001 budget, the IWGN recommends a national initiative. The initiative, known as **NTR (Nanotechnology for the Twenty-First Century: Leading to a New Industrial Revolution)**, will approximately double the Federal Government's annual investment in nanotechnology research and development from its present (FY99) base of $234M per year. The increase will be incrementally grown over a three-year interval.

The NTR Initiative will address five activities:

- Long-term nano science and engineering research that will lead **to fundamental understanding and to discoveries of novel phenomena, processes and tools for nanotechnology**. This commitment will refocus the government investment beginning in the 1950s that led to today's microelectronics, microfabrication, and computer technology;

- Synthesis and processing "by design" of engineered, nanometer-size, material building blocks and system components, fully exploiting molecular self-assembly concepts. This commitment will generate new classes of high performance materials, bio-inspired systems, paradigm changes in device design, and efficient, affordable manufacturing of high performance products. Novel properties and phenomena will be enabled, as control of structures of atoms, molecules and clusters becomes possible;

- Nanodevice concepts including system architecture research to best exploit nano-derived properties in operational systems, and combining building-up of molecular structures with ultraminiaturization. The new nanodevices will cause orders of magnitude improvements in microprocessors and mass storage, create tiny medical tools that minimize collateral damage; and enable uninhabited defense combat vehicles in fully imaged battle fields. There will be dramatic payback to programs with this National priority including **information technology, nanobiotechnology and medical technology**;

- Application of nanostructured materials and systems to manufacturing, power systems, energy, environment, national security, and health. Areas of interest include advanced dispersions, catalysts, separation methods, and consolidated nanostructures, as well as increase the pace of knowledge and technology transfer;

- Educate and train a new generation of skilled workers in the multidisciplinary perspectives necessary for rapid progress in nanotechnology.

Potential for NTR impact is compelling:

- Nano science and engineering **knowledge is exploding worldwide** because of the availability of new investigative tools; maturity in the biology, chemistry, engineering, materials and physics disciplines, and interdisciplinary synergism; and financial support driven by emerging technologies and their markets. The science and engineering communities have generated a flurry of new results, doubling the publication rate each two-three years. During 1998, funding agency initiatives in nanotechnology (NSF Functional Nanostructures Initiative, and DoD Multidisciplinary University Research Initiative in Nanoscience) had success rates no higher than 1 in 6, constrained only by funding limitations;

- The nanotechnology revolution will lead to **fundamental breakthroughs** in the way materials, devices and systems are understood, designed and manufactured. Dr. Neal Lane stated at a Congressional hearing in April 1998 that, *"If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering."* Potential breakthroughs include orders-or-magnitude increases in computer efficiency; emergence of entirely new phenomena in physics and chemistry; nanofabrication of three-dimensional molecular architectures; novel processing architectures such as quantum computing and cellular automata; repair of human body with replacement parts; and a virtual presence in space;

- Nanotechnology is creating a **technology revolution** in the way materials, devices and systems are manufactured and perform. In the last few years, applying fundamental discoveries has developed multi-billion dollar product lines. These include: giant magnetoresistance multilayers (for computer memory), nanostructured coatings (in data storage and photographic industry), nanoparticles (colorants in printing and drug delivery in pharmaceutical field), superlattice confinement effects (for optoelectronic devices and lasers), and nanostructured materials (nanocomposites and nanophase metals). John Armstrong, formerly Chief Scientist of IBM, wrote in 1991, *"I believe nanoscience and nanotechnology will be central to the next epoch of the information age, and will be as revolutionary as science and technology at the micron scale have been since the early '70s."* More recently, industry leaders including those at the IWGN workshop on Jan. 27-29, 1999, have extended this vision by concluding that nanoscience and technology will change the nature of almost every human-made object in the next century;

- Nanoscience is an opportunity to **energize the interdisciplinary connections** between biology, chemistry, engineering, materials, mathematics, and physics in education. It will give birth to new fields that are only envisioned at this moment;

- European and Pacific countries have developed focussed programs in the science and technology of nanostructures that will provide **world-wide critical mass** to this initiative, accelerate progress, and guarantee commercial competition for the results.

NTR investment strategy:

- This initiative **builds on previous and current nanotechnology programs**, including some early investment from the Advanced Materials Processing Program, NSF instrumentation and functional nanostructures, and DoD programs supporting its Nanoscience Strategic Research Objective;

- The lead-time for science maturing into technology is approximately 10-15 years; now is a critical time for government investment in the S&T of nanostructures. The leaders from industry, academe and government present at the IWGN Workshop concluded that the Federal Government was underinvesting in **long-term nanotechnology research and development** relative to the outstanding opportunities. The private sector is unlikely to invest in nano science and engineering research until products are 3-5 years from commercialization;

- Roughly *70 percent of the funding will be for university-based research*, which will also help meet the demand for skilled workers with advanced nanotechnology skills in the next century. In the academic programs, it is anticipated that 65% of the funding will be for single investigators, 15% multidisciplinary programs and *5-10% for nanotechnology centers that will play a similar role to the supercomputer centers*, 5-10% instrumentation development and procurement, and 5% for the development of multidisciplinary educational programs. Government/industry/academic partnerships will be strongly encouraged.

Draft **NANOTECHNOLOGY – A REVOLUTION IN THE MAKING** **Draft**

- VISION FOR R&D IN THE NEXT DECADE -

Interagency Working Group on Nano Science, Engineering and Technology (IWGN)
Dr. M. Roco, IWGN Chair, mroco@nsf.gov; Dr. J. Murday, IWGN Exec Sec, murday@ccf.nrl.navy.mil

Abstract:

A national initiative, "Nanotechnology for the Twenty-First Century: Leading to a New Industrial Revolution", is recommended as part of the fiscal year 2001 budget. The initiative will support long-term nanotechnology research and development, which will lead to breakthroughs in information technology, advanced manufacturing, medicine and health, environment and energy, and national security. The impact of nanotechnology on the health, wealth and lives of people will be at least the equivalent to the combined influences of microelectronics, medical imaging, computer-aided engineering and man-made polymers developed in this century. The proposed level of additional annual funding approximately doubles (by $260 M) the current level of effort, incrementally increased over three years. This initiative will focus on fundamental research on novel phenomena, processes and tools; synthesis and processing by design; nanostructured devices, materials and systems that are high risk, broadly enabling and are designed to have major impact; as well as education and training of future nanotechnology workers and rapid knowledge and technology transfer.

Contents:

1. Nanotechnology Definition

Nanotechnology is concerned with materials and systems whose structures and components exhibit novel and significantly improved physical, chemical and biological properties, phenomena and processes because of their small nanoscale size. Structural features in the range of about 10^{-9} to 10^{-7} m (1 to 100 nanometers) determine important changes as compared to the behavior of isolated molecules (1 nanometer) or of bulk materials. For comparison, 10 nanometers are 1000 times smaller than the diameter of a human hair.

We can exploit novel properties and phenomena of nano-based entities as we gain control of structures and devices at the atomic, molecular and supramolecular levels, and as we learn how to efficiently manufacture and use these devices. New behavior at the nanoscale is not necessarily predictable from that observed at large size scales. Important changes in behavior are caused not by the order of magnitude size reduction, but also by new phenomena such as size confinement, predominance of interfacial phenomena, quantum mechanics and Coulomb blockade. It is notable that all relevant phenomena at nanoscale are caused by the tiny size of the organized structure as compared to molecular scale, and by the interactions at their predominant and complex interfaces. Once we are able to control feature size, we can enhance material properties and device functions beyond those that we currently know or even imagine. Reducing the dimensions of structures leads to entities with novel properties, such as carbon nanotubes, quantum wires and dots, thin films, DNA based structures, and laser emitters. Such new forms of materials and devices herald a revolutionary age for science and technology provided that we can discover and fully utilize the underlying principles.

2. Revolution in the Making: Driving Forces

In 1959 Richard Feynman delivered a now famous lecture, "There is Plenty of Room at the Bottom." He stimulated his audience with the expectation of exciting new discoveries if one could fabricate materials and devices at the atomic/molecular scale. For this to happen, he pointed out the necessity of a new class of miniaturized instrumentation to manipulate and measure the properties of these small structures—nanostructures.

It was not until the 1980s that miniaturization of instruments actually surfaced in developments like scanning tunneling microscopes, force microscopies and near field microscopes. These instrument classes exploited microfabrication technology to enable nanometer resolution—a wide variety of the "eyes" and "fingers" required for nanostructure measurement and manipulation. In a parallel development, augmented computational capability now enables sophisticated computer simulations of nanostructures. These new techniques have sparked excitement in nearly all parts of the scientific community. Traditional models and theories for most material properties and device operations involve assumptions leading to "critical scale lengths" that are frequently larger than 100 nm. When the dimensions of a material structure is under the respective critical length scale, then the models and theories are not able to describe the novel phenomena. Scientists in all materials and technology disciplines are in avid pursuit of the fabrication and measurement of nanostructures to see where and what kind of interesting new phenomena occur. Further, nanostructures offer a new paradigm for materials manufacture by assembling (ideally utilizing self-organization and self-assembly) to create an entity rather than the laborious chiseling away from a larger structure.

Strong financial support for this research and development is motivated by the impressive potential for economic return, including continued improvement in electronics/electrooptics for information technology; higher performance, low maintenance materials in manufacturing, defense, space and environmental applications; and acceleration of biotechnology for medical, health and agricultural uses. John Armstrong, formerly Chief Scientist of IBM, wrote in 1991, *"I believe nanoscience and nanotechnology will be central to the next epoch of the information age, and will be as revolutionary as science and technology at the micron scale have been since the early '70s."* More recently, industry leaders including those at the IWGN workshop on Jan. 27-29 have extended this vision by concluding that nanoscience and technology will change the nature of almost every human-made object in the next century. Such significant improvements in materials performance and changes in manufacturing paradigms will lead to an industrial revolution.

Federal support of the nanotechnology infrastructure is necessary to enable the U.S. to compete in the global marketplace.

3. Nanotechnology Impact

The potential benefits of nanotechnology are pervasive:

Information Technology. The Semiconductor Industry Association (SIA) has developed a roadmap for the continued enhancements in miniaturization, speed and power consumption reduction of information processing devices—sensors for signal acquisition, logic devices for processing, storage devices for memory and displays for visualization. The roadmap projects the future to approximately 2010 and to 0.1-micron (100 nm) structures, just short of nanostructure devices. There are several reasons why it stops at 100 nm. First, it is not clear how to economically fabricate nanostructured electronics. Second, even if fabricated, the physical/chemical properties of those nanostructures are unknown; the present electronic devices are all based on models with critical scale lengths in the 100+ nm range. Third, without known properties it is impossible to design a functional device, fabricate and assemble the devices into a working system. The SIA roadmap explicitly calls for "sustained government support if this industry is to continue to provide for strong economic growth in the U.S." The lead-time for science maturing into technology is approximately 10-15 years; so now is the critical time for government investment in the science and technology of nanostructures for timely impact in information technology. Further, the investment will have spin-offs that enable the attainment (or acceleration) of the roadmap goals. The area of magnetic information storage is illustrative. Within ten years of the fundamental discovery of the new phenomenon of giant magnetoresistance, this new nanotechnology completely replaced older technologies for disk computer heads in the $34 B/yr hard disk market (1998). Other potential breakthroughs include: (a) orders of magnitude improvement in microprocessors - nanostructured transistors will continue the trend in lower cost per transistor and use less energy, thereby improving the efficiency of computers by a factor of millions; (b) changes in communications paradigms as higher frequencies (faster speeds) provide 10 times more bandwidth, with consequences in business, education, entertainment and defense; (c) expansion of small mass storage devices to multi-terabit capacities, 100 times better than today; and (d) integrated sensor systems that collect data utilizing minimal power, space and weight. Applications include: (a) affordable virtual reality stations to provide individualized teaching aids (and entertainment), (b) sufficient computational capability to enable uninhabited combat vehicles (and civilian transportation), and (c) communication capability that obviates much business travel (including commuting to a work place) in an era when transport fuels will be dramatically more expensive.

Medicine & Health. Living systems are governed by molecular behavior at nanometer scales where the disciplines of chemistry, physics, biology and computer simulation all now converge. Such multidisciplinary insights will stimulate nanobiotechnology progress far beyond its already impressive record of accomplishments in medicine and health over the last ten years. The molecular building blocks of life - proteins, nucleic acids, lipids, carbohydrates and their non-biological mimics - are examples of materials that possess unique properties determined by their size, folding and patterns at the nanoscale. We can now probe single molecule properties; this new information will complement (and largely supplant) the ensemble average techniques of present day life sciences. New analytical tools capable of probing the nanometer world will also make it possible to characterize chemical and mechanical properties of cells, of interest in cellular biology and pathology, including processes such as cell division, metabolism, regulation and locomotion. Utilization of nanofabricated surfaces and devices will increase the speed of genome sequencing by orders of magnitude, and thus our ability to probe and decode the fundamental nature of living systems. Coupling these advances in our knowledge of living systems, with the unique capabilities imparted by nanostructures and materials, we will be in a position to detect and intervene in pathology and disease using biologically inspired systems. Integration of biocompatible materials with fluidic, optic, mechanical and electronic components, all at micro to nano scale, will enable development of in vivo-implantable devices. For example, remote, non-invasive sensing systems will allow us to detect the earliest stages of emerging disease, whether caused by infection or tissue malfunction, and prevent overt disease development. Such early sensing will be coupled to better means of intervention such as coated particles to provide new routes for drug delivery, nano surgical approaches, and implantable drug synthesis and delivery systems, making prevention and therapy less costly, less traumatic for patients, and more effective. Applications include: (a) Rapid, efficient genome sequencing, which will permit the characterization of each individual's genetics, thereby enabling a revolution in diagnostics and therapeutics; (b) Intracellular sensors, which will allow for further understanding of the basic properties of living (normal and diseased) cells; (c) New formulations and routes for drug delivery, which will enormously broaden their therapeutic potential by effecting delivery of new types of medicine to sites in the body that were previously inaccessible; (d) More durable, rejection-resistant artificial organs will be developed from new biocompatible, high performance materials based on their surface nanostructure; (e) Sensing systems, which will allow the detection of emerging disease in the living body, and will ultimately shift the focus of patient care from disease treatment to early detection and/or prevention.

Materials and Manufacturing. Nanotechnology is fundamentally changing the way materials and devices will be produced in the future, including ceramics, metals, polymers, and their composites. The ability to synthesize nanoscale building blocks with precisely controlled size and composition and then to assemble them into larger structures with unique properties and functions will revolutionize segments of materials manufacturing. At present we perceive only the tip of the iceberg in terms of the benefits that nanostructuring can bring: lighter, stronger, and programmable materials, reductions in life-cycle costs through lower failure rates, innovative devices based on new principles and architectures, and use of molecular/cluster manufacturing. Molecular/cluster manufacturing takes advantage of assembly at the nanoscale level for a given purpose. Structures not previously observed in the nature can be developed. Challenges include: synthesis of materials by design, developments of bio- and bio-inspired materials, development of cost-effective and scalable production techniques, and determination of the nanoscale initiators of materials failure. Applications include: (a) net-shape manufacturing of nanostructured metals and ceramics; (b) improved printing brought about by nanometer-scale particles that have the best properties of both dyes and pigments; (c) nanoscale cemented and plated carbides and nanocoatings for cutting tools, electronic, chemical and structural applications; and (d) nanofabrication on a chip with high levels of complexity and functionality.

Aeronautics and Space Exploration. The stringent fuel constraints for lifting payloads into earth orbit and beyond, and the desire to send spacecraft away from the sun (diminished solar power) for extended missions, compel continued reduction in size, weight and power consumption of payloads. Nanostructured materials are also critical to lightweight, high-strength, thermally stable materials for planes, rockets, space station and planetary/solar exploratory platforms. The low gravity, high vacuum space environment may help develop nanostructures and assembled nanostructures that cannot be created on Earth. Applications include: (a) Low power, radiation hard, high performance computers; (b) Nanoinstrumentation for microspacecraft; (c) Avionics; and (d) Thermal barrier and wear resistant nanostructured coatings.

Environment and Energy. Nanotechnology will have potentially significant impacts on energy efficiency, storage and production. It can be used to monitor and remediate environmental problems; improve control emissions from a wide range of sources, and develop new, ‘green’ processing technologies that minimize the generation of undesirable by-products. The impact on industrial control, manufacturing and processing will be impressive and result in saving energy. Several technologies, developed without the benefit of the new nanoscale analytical capabilities or in development, illustrate that potential: (a) The Mobil Oil Co. long-term research program into the use of crystalline materials as catalyst supports has yielded catalysts with well defined pore sizes in the range of 1 nm; their use is now the basis of an industry that exceeds $30 B/yr; (b) The discovery of the ordered mesoporous material MCM-41 by the Mobil Oil Co., with pore size in the range 10 to 100 nm, that is widely applied in removal of ultrafine contaminants; (c) The Dow Chemical Co. has developed a nanoparticle-reinforced polymeric material that can replace metallic components in the auto industry; the wide spread use of those nanocomposites could lead to a reduction of 1.5 billion liters of gasoline consumption over the life of one year’s fleet of vehicles and reduce the related dioxide emissions by more than five billion kilograms; (d) the replacement of carbon black in tires by nanometer-scale particles of inorganic clays and polymers is a new technology that is leading to the production of environmentally-friendly wear-resistant tires. Potential future breakthroughs also include use of nano-robotics and intelligent systems for environment and nuclear waste management.

National Security. The Department of Defense recognized the importance of nanostructures over a decade ago and has played a significant role in nurturing the field. Critical defense applications include: (a) Continued information dominance, identified as an important capability for the military, will depend on U.S. nanotechnology. (b) Nanostructured electronics will provide more sophisticated virtual reality systems that enable affordable, effective training. (c) Reduction in military manpower must be compensated by the increased use of nanostructure-enhanced automation and robotics, both of which will benefit from nanostructures. The use of uninhabited combat vehicles is desired, both to reduce risk to human life as well as to improve vehicle performance. For example, several thousand pounds could be stripped from a pilotless fighter aircraft, resulting in longer missions. In addition, the fighter agility could be dramatically improved without the necessity to limit g-forces on the pilot, increasing its combat effectiveness. (d) Nanostructured materials hold the promise for the high performance (lighter, stronger) needed in military platforms while simultaneously providing diminished failure rates and lower life-cycle costs. (e) Advances in medicine and health enabled by nanoscience will provide badly needed chemical/biological/nuclear sensing, protection and improvements in casualty care. (f) Changes are also possible in the design and weight reduction of nuclear weapons and systems used in non-proliferation.

Other Applications. Potential benefits from nano science and technology affect other government agency missions, including: (a) more economical and reliable transportation systems (DOT), (b) measurement, control and remediation of contaminants (EPA), (c) forensic research (DOJ), and (d) printing and engraving (BEP).

Global Trade and Competitiveness. Technology is the major driving factor for growth at every level of our economy. Nanotechnology is expected to be pervasive and ubiquitous in its applications across all technologies. Investment in nanotechnology research and development is necessary to maintain and improve our position in the world marketplace. This initiative will allow the development of critical enabling technologies with broad commercial potential. These enabling technologies include manufacturing and the measurement and standards tools necessary for U.S. industry to take advantage of nanotechnology innovations and improve our capability to compete globally.

Science and Education. The science, engineering and technology of nanostructures will require and enable advances in a fabric of disciplines: physics, chemistry, biology, mathematics and engineering. In their evolution as disciplines they all find themselves simultaneously ready to effectively address nanostructures. This provides an unprecedented opportunity to revitalize the connections between physics, mathematics, chemistry, biology and engineering in education. The dynamics of the interdisciplinary nanostructure efforts will revitalize educational connections between disciplines and will give birth to new fields that are only envisioned at this moment. This opportunity requires change in the laboratory and human resource infrastructure in universities, and in the education of nanotechnology professionals, especially for industry.

4. Investment Opportunities

Nanoscale science and engineering knowledge is exploding worldwide because of the availability of new investigative tools and interdisciplinary synergism, and is driven by emerging technologies and their applications. New experimental and modeling tools have made possible such discoveries, opening windows of research opportunities. The number of revolutionary discoveries reported in nanotechnology can be expected to accelerate in the next decade, and is likely to profoundly affect existing and emerging technologies in almost all industry sectors and application areas, including computing and communications, pharmaceuticals and chemicals, environmental technologies, energy conservation, manufacturing and healthcare-related technologies. As a result of the highly competitive and dynamic characteristic of nanotechnology and of the potential high return on investment, the opportunity to establish a special initiative is significant. There is a clear need to create a balanced infrastructure for nanoscale science, engineering, technology and human resources development in this revolutionary field.

The reported Federal Government expenditure for nanotechnology in fiscal year 1997 was $116 M (WTEC Study, 1998; Nanotechnology as defined there only included work to generate and use nanostructures and nanodevices; it did not include the simple observation and description of phenomena at the nanoscale that is part of nanoscience). It is estimated to be at over $230 M in fiscal year 1999. A much greater investment could be utilized effectively. Funding agencies and professional societies are experiencing a flurry of new results in nanotechnology, and a growing interest within the research community. The funding success rate for the small-group interdisciplinary research program, FY98 NSF "Functional Nanostructures" initiative, was about 13% (lower if one considers the limitation of two proposals per university). The success rate for the DoD 1998 MURI initiative on nanostructures was 17% (5% if one starts with the number of white papers submitted to guide proposal development).

The promise of nanotechnology must be realized through a balanced investment:

- Nanostructure Properties: develop and extend our understanding of biological, chemical, electronic, magnetic, optical, and structural properties in nanostructures.
- Synthesis and Processing: enable the atomic and molecular control of material building blocks, and engineering that provides the means to assemble and utilize these tailored building blocks for new processes and devices in a wide variety of applications. Extend the traditional approaches to patterning and microfabrication to include parallel processing with proximal probes, stamping and embossing. Particular attention must be given to the interface with bionanostructures and bio-inspired structures, multifunctional and adaptive nanostructures, scaling approaches, and affordability at commercial scales.
- Characterization and Manipulation: new experimental tools to broaden the capability to measure and control nanostructured matter, including the development of new standards of measurement. Particular attention must be given to tools capable of measuring/manipulating single macro- and supra-molecules of biological interest.
- Modeling and Simulation: accelerate the application of high performance computation to the prediction of nanostructured properties and phenomena, and materials by design.
- Device and System Concepts: stimulate the innovative application of nanostructure properties in ways that might be exploited in new technologies.

International Perspective: The U.S. does not dominate nanotechnology research. There is strong international interest, with nearly twice as much research ongoing overseas as in the United States. Other regions, particularly Japan and Europe, are supporting work that is equal to the quality and breadth of the science done in the U.S. because they have determined that nanotechnology has the potential to be a major economic factor during the next several decades. This situation is unlike the other post-war technological revolutions, where U.S. enjoyed earlier advances. The 1991 Congressional Office of Technology Assessment report, Miniaturization Technologies, states *that "the competitive position of U.S. R&D in miniaturization technology remains strong, although competition from Japanese and European industry and governments has increased."*

The international dimensions of nanotechnology research and its potential applications implies that the United States must put in place an infrastructure that is equal to that which exists anywhere in the world. This emerging field also creates a unique opportunity for the United States to partner with other countries in ways that are mutually beneficial through information sharing, cooperative research, and study by young U.S. researchers at foreign centers of excellence. A suitable U.S. infrastructure is also needed to compete and collaborate with those groups.

5. High-level Recognition of the Potential

The potential of this technology has not passed unnoticed. Then-Senator Gore held the first hearing on nanotechnology in 1992. The Defense Department identified nanotechnology as a strategic research objective in 1997, and NSF has highlighted nanoscale science and technology in its fiscal year 1999 budget. In March 1998, the President's Science Advisor Dr. John H. Gibbons identified nanotechnology as one of the six technologies that will determine economical development in the next century. Dr. Neal Lane, former NSF director, stated at a Congressional hearing in April 1998 that, *"If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering."*

Expert opinions in industry and academia (e.g. PCAST, National Academy, industry and professional organizations) on research needs and opportunities should be collected.

6. A National Initiative: Leading to New Industrial Revolution

Role of Government in nano science and technology: Nanotechnology research is in an early stage and has several promising results. It is clear that it can have a substantial impact on industry and on our standard of living. But investments must be made in the basic science and technologies that will enable scientists and engineers to invent totally new technologies and enable industry to produce cost-competitive products. Much of the results on nanostructures and nanoprocesses are not yet fully measurable, replicable or understood, and will require many years to develop corresponding technologies. Industry is unable in the 3-5 year industrial product time frame to effectively develop cost competitive products out of current knowledge. Fundamental nanotechnology research and development is too costly, long-term and risky for private industry to undertake. There are critical areas of research and development that are being ignored by industry or have significant underinvestment. Companies will not provide the investment needed to establish the nanoscience infrastructure and to fund long-term research needed to realize the potential. The fundamental infrastructure that industry uses to develop new products needs to be strengthened and expanded.

Nanotechnology cannot flourish without strong supporting science programs because of the scale and complexity of the nanosystems. Nanotechnology research is the USA has been developed in open competition with other research topics within various disciplines. This is one of the reasons that the USA research efforts in nanotechnology are relatively fragmented and partially overlapping among disciplines, areas of relevance, and sources of funding

Therefore, the Federal Government needs to invest in the infrastructure necessary for the United States to lead and benefit from the revolution that is coming. It needs to expand university and national laboratory facilities, build the workplace skills necessary to staff future industries based on nanotechnology, encourage cross-disciplinary networks and partnerships, ensure the distribution and spread of information, and encourage small businesses to develop the instruments and tools needed.

Nanotechnology R&D requires long-term investment: Nanoscience and engineering will need a long-term investment because of the interdisciplinary characteristic, limitations of the existing experimental and modeling tools in the intermediate range between individual molecules and bulk, and the need for technological infrastructure. The time from fundamental discovery to market is typically 10-15 years (see for instance the application of magnetoresistance by IBM, and of mesoporous silicate by Mobil Oil Co.). Historically, industry becomes a major player only in the last 3-5 years, when the investments are much larger than in the previous period but the economic return more certain. Government leadership and funds are needed to establish the infrastructure and research support in the first 7-12 years. Since major industrial markets are not yet established for nanotechnology products, the government should also support technology transfer activities to accelerate the long-term benefits.

Technological innovation and commercialization is taking place at an ever-increasing pace. The enabling infrastructure and technologies must be in place for industry to take advantage of nanotechnology innovations and discoveries. Industry is frequently reluctant to invest in risky research that takes many years to develop into a product. In the U.S., the government and university research system fills this gap. The increasing pace of technological commercialization requires a compression of past time scales and parallel development of research and commercial products and a synergy among industry, university, and government partners.

The priority research areas for additional funding in FY2001 are:

- Long-term nano science and engineering research that will lead to **fundamental understanding and to discoveries of novel phenomena, processes, experimental and simulation tools for nanotechnology**. This commitment will rival and refocus the government investment beginning in the 1950s that led to today's microelectronics, microfabrication, and computer technology; (Request $75M);
- **Synthesis and processing "by design"** of engineered, nanometer-size, material building blocks and system components, fully exploiting self organization concepts. This commitment will generate new classes of high performance materials, bio-inspired systems, changes in device design paradigms, and efficient, affordable manufacturing of high performance products. Novel properties and phenomena will be enabled, as control of organizational structures of atoms, molecules and clusters becomes possible; (Request $60M);
- **Nanodevice concepts** including system architecture research to best exploit their properties in operational systems, and combining building-up of molecular structures with ultraminiaturization. The nanodevices will cause paradigm changes such as order-of-magnitude improvements in microprocessors and mass storage, overall selective drug and gene delivery systems, use of tiny medical tools that minimize collateral damage; and uninhabited defense combat vehicles in fully imaged battle field. There will be dramatic payback to programs with National priority including information technology, nanobiotechnology and medical technology; (Request $58M)
- **Application of nanostructured materials and systems** to manufacturing, power systems, energy, environment, national security, and health. Areas of interest include advanced dispersions, catalysts, separation methods, and consolidated nanostructures; Develop core enabling technologies such as fundamental molecular scale measurement and manipulation tools and standard methods, materials, and data that will be applied to many commercial sectors (Request $58M);
- **Educate and train a new generation of skilled workers** in the multidisciplinary perspectives necessary for rapid progress in nanotechnology; (Request $10M)

Common Themes:

Funding modes:

- Need for sustained support to individual investigators and small-groups doing fundamental, innovative research; Larger investment should be given at the beginning to funding fundamental research, as well as to development of university-industry-laboratories and interagency partnerships;
- Interdisciplinary and the need for correspondingly appropriate funding modes (interdisciplinary programs, centers and networks);

- Encourage research and users' networks; The establishment of 5-10 nanotechnology research centers similar to the supercomputer centers will play an important role in development and use of the specific tools in the next decade, and in promoting partnerships. An expansion of the existing NNUN users network may be considered. Two thirds of the funds will be used for individual and small group investigators;
- Encourage university-industry-national labs and international collaborations. Knowledge and technology transfer between universities and industry will be encouraged. Develop enabling infrastructure so that new discoveries and innovations can be rapidly commercialized by U.S. industry.

Research areas:
- Nanoelectronics and information technology
- Multi-scale, hierarchical modeling and simulation of nanostructures and nanoprocesses
- Development of experimental methods and devices to measure various properties and phenomena at nanoscale; Combine measurement, manipulation and manufacturing tools;
- Connection to biology (biostructures & bio-inspired systems)
- Synthesis, assembly and processing of nanostructured materials 'by design'
- System architecture and devices
- Focus on fundamentals that are broadly enabling of many areas of technology and that help industry to develop new competitive, profitable products that industry would not develop on its own.

Partnerships:
- Among disciplines (small group research)
- Among institutions & types of institutions (e.g., universities, industry, government labs)
- Among countries
- Among U.S. government funding agencies and states; support for complementary activities
- Joint funding and use of centers (facilities)
- International collaborations to promote access to centers of excellence abroad, visits by young researchers abroad, and bilateral and multilateral agreements

Infrastructure Needs for Nanotechnology: The nanotechnology initiative requires a balanced, predictable, strong, but flexible infrastructure to stimulate the further rapid growth of the field. Ideas, concepts and techniques are moving at such an exceedingly rapid pace that the field needs coordination and focus from a national perspective. Demands are high and the potential is great for universities and government to continue to evolve and transition this science and technology to bring forth the changes in technology that will enable U.S. industry to commercialize many new products in all sectors of the economy. Even greater demands are on industry to attract new ideas, protect intellectual property, and develop appropriate products. This field has major multidisciplinary aspects, which are difficult to coordinate in a formless fashion. If these issues are not addressed, the United States will fall behind world developments and, therefore, have difficulty maintaining the economy and quality of life and security that exist today.

Tools must be provided to investigators in nanotechnology for them to carry out state-of-the-art research to achieve this potential and remain competitive. The tools will include but not be limited to such items as ion beam neutron and photon sources, instruments for manipulation, new forms of lithographs, computational capabilities and other systems to characterize the nano-scale systems. Centers, with multiple grantees or laboratories, where these tools would be available for this support should be established at a level of several million dollars annually. These centers should also have the diverse research teams that will be effective in different scientific disciplines. We should also investigate means to achieve the remote use of these facilities. Funding mechanisms that encourage centers, university, laboratory, industrial collaboration should be emphasized, as well as single investigators who are tied into these networks. One of the major potential barriers of cooperative efforts is intellectual property rights.

Support to single investigators for their competence and imaginative programs should provide a corresponding level of personnel support and equipment. University grants should encourage work among research groups to make maximum use of concepts and ideas being developed in other disciplines. The infrastructure includes building links between researchers, developers and users of nanotechnology innovations. The initiative will develop critical enabling technologies that will have significant value added in many industries. The initiative will allow U.S. industry to develop new profitable products that will maintain and improve our global competitiveness in short (3-5 years) and long term.

It will be necessary to fund training of students and support of postdocs under fellowships that will attract some of the best students available. This is extremely important considering the rapid change in the research. Students should receive multidisciplinary training in various nanotechnology fields. Both organizational attention and funding should also be devoted to ensuring the open exchange of information in multidisciplinary meetings and rapid publication of results, through, for example, workshops and widely disseminated summaries of research.

Because of the fast evolving nature of nano-technology and its importance to our society, the program management must be flexible with the capability of changes needed. Working groups to make recommendations to modify the program as it evolves should be supported.